



# tinyGTC GPSDO

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Design, Simulation and Validation

# Content

- tinyGTC and its internal reference
- Problem: Oscillator (in)Stability
- Solution: GPS time/frequency transfer
- Design: Components and Architecture
- Simulation
- Validation

# tinyGTC Internal reference

Reference for time and frequency measurement

Can be output for usage by other equipment.

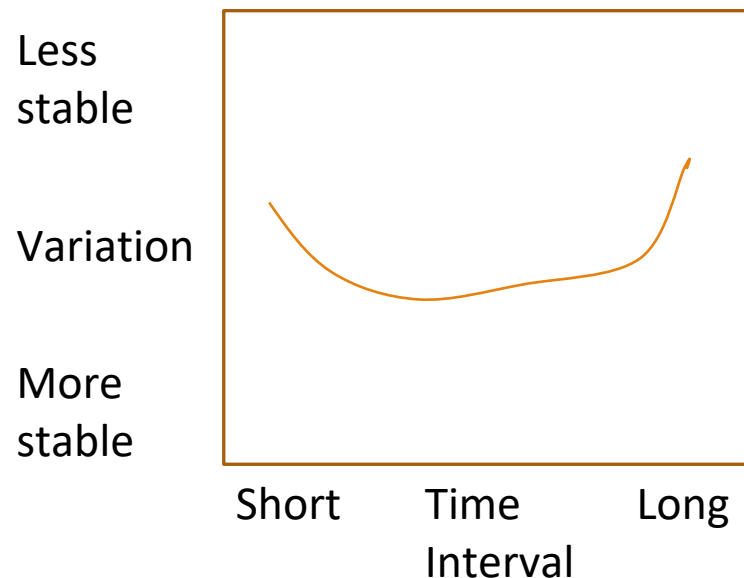
Design constraints:

- Cost : Must be fraction of total cost.
- Size: Has to fit on SMD PCB in small enclosure.
- Power consumption: Allow least 5 hours battery life.
- Speed: Frequency error below  $1e-9$  within 1 minute
- Stability: Preferably matching with tinyGTC accuracy.

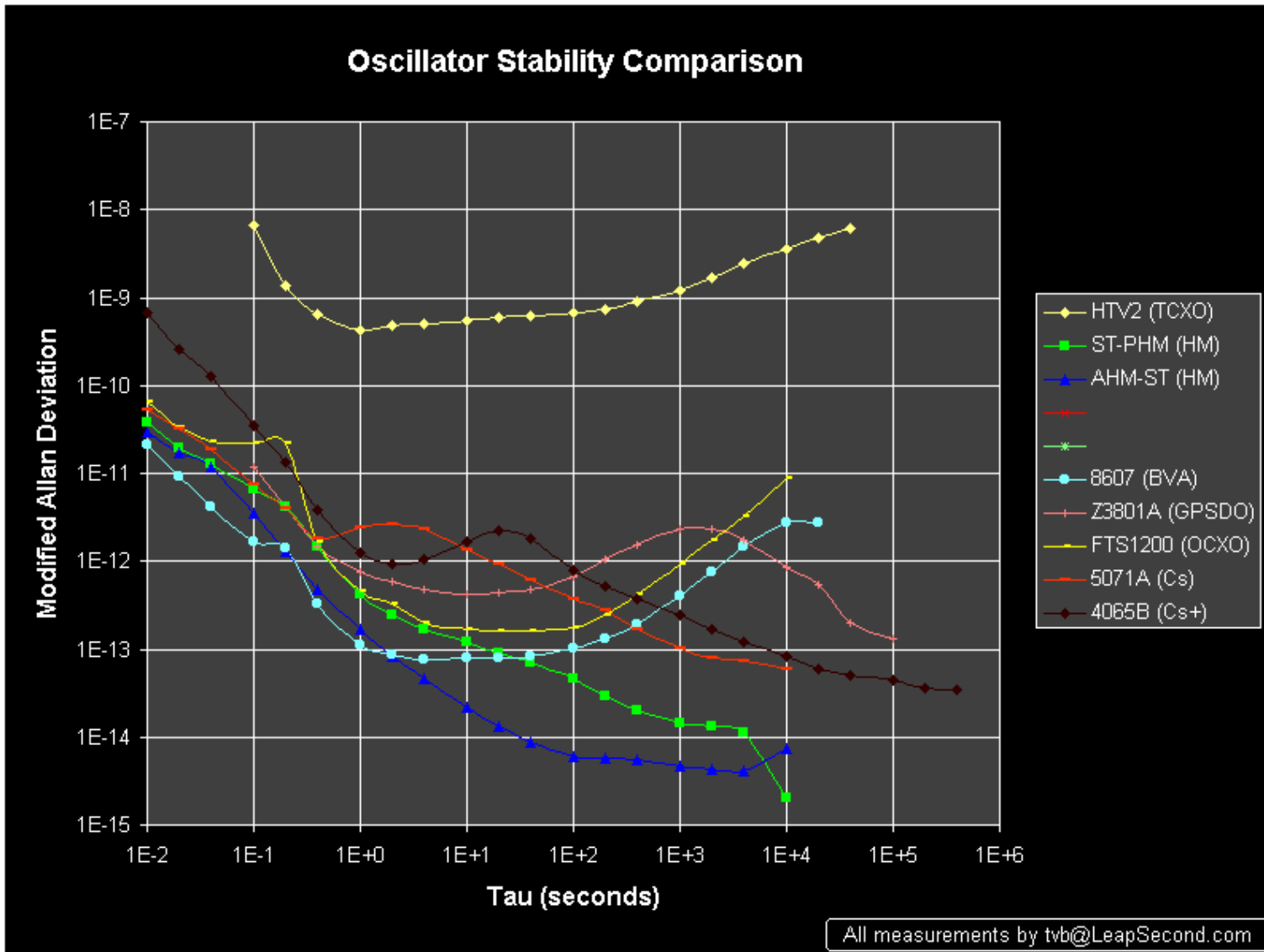
# Presenting oscillator stability

## Understanding ADEV

- Allan Deviation (ADEV) computes the
  - **Average difference (Variation)** of two measurements versus the
  - **Time interval** between the two measurements
- Often plotted in Log-Log scale of Variation versus Time Interval
- The level of Variation can also be called the level of Stability
- ADEV number is meaningless without mentioning the interval at which it is measured
- ADEV =  $1e-10$  @ 1 s means:
  - Average  $1e-10$  variation
  - When measured over a 1 s interval
- ADEV can also be used for a counter
  - Specifies error level over an interval
  - $1e-10$  @ 1 s = 10 digits / s
  - Reality is more complex



# Typical stability of oscillators

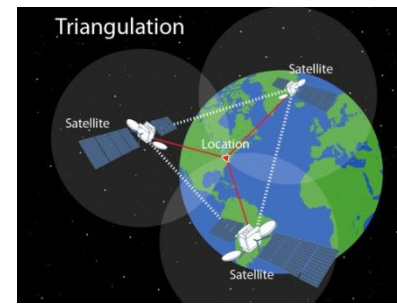


# Typical stability of oscillators

Technology	Stability	Up to	Power	Cost
XO	1e-6 to 1e-7 @ 1 s	10 s	0.01 W	0.5 \$
TCXO	1e-9 to 1e-10 @ 1s	100 s	< 0.1 W	1 \$
OCXO	1e-10 to 1e-12 @ 1s	1000 s	3 W	25 \$
Rubidium	1e-13 @ 1 day	1e-11 / month	15 W	400 \$
Cesium	1e-14 @ 1 day	<< 1e -11 / month	40 W	1500 \$
H Maser	1e-15 @ 1 day	<< 1e-11 / month	500 W (?)	> 100 k\$

- Long term drift is the biggest limitation with cheaper oscillators
- If it would be possible to “transfer” time from a remote accurate oscillator to the tinyGTC it would be possible to “adjust” a less accurate oscillator to eliminate the long term instability
- How about GPS?

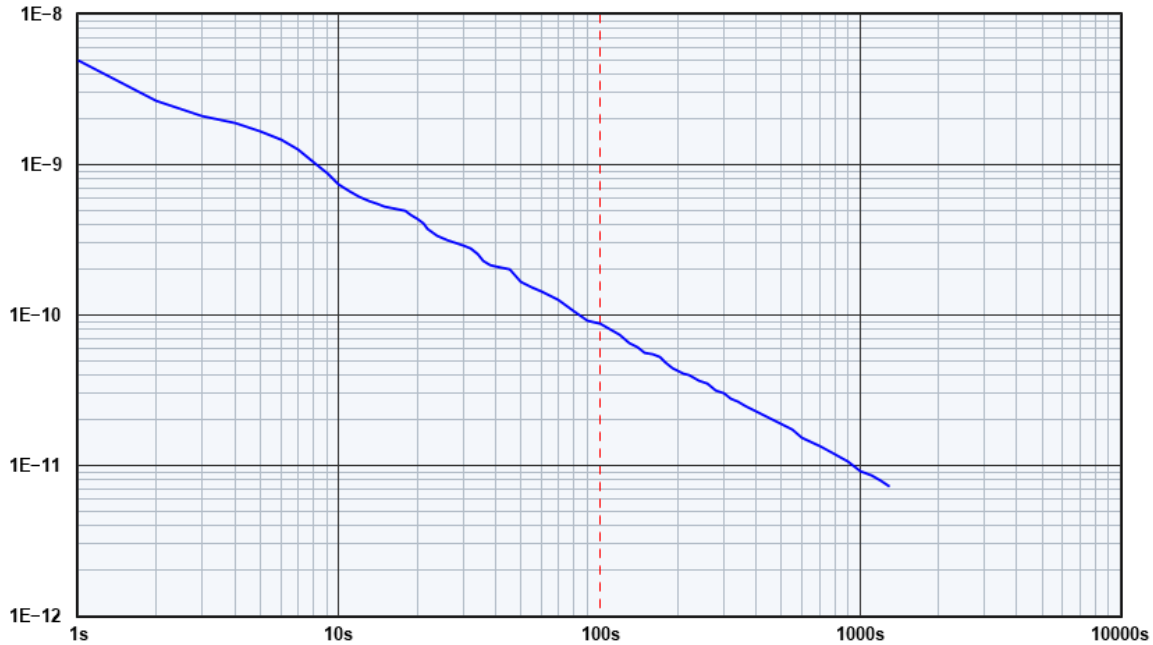
# GPS system



- Each GPS satellite contains a Cesium clock, synced to common “GPS” time, and broadcasts its time and position.
- Positioning of GPS receiver based on triangulation to at least 3 satellites using difference of received time due to speed of radio waves and distance to satellite.
- GPS receiver can also calculate the “GPS” time and output a pulse at the start of each “GPS” time second.
- tinyGTC can timestamp PPS with 4 ns accuracy without added HW and compare with time derived from internal reference.
- Can this timestamp be used to discipline a oscillator?
  - Yes! This is called a GPS Disciplined Oscillator (GPSDO)
  - But what is the quality of this timestamp?

# Typical cheap GPS PPS ADEV

Allan Deviation  $\sigma_y(\tau)$



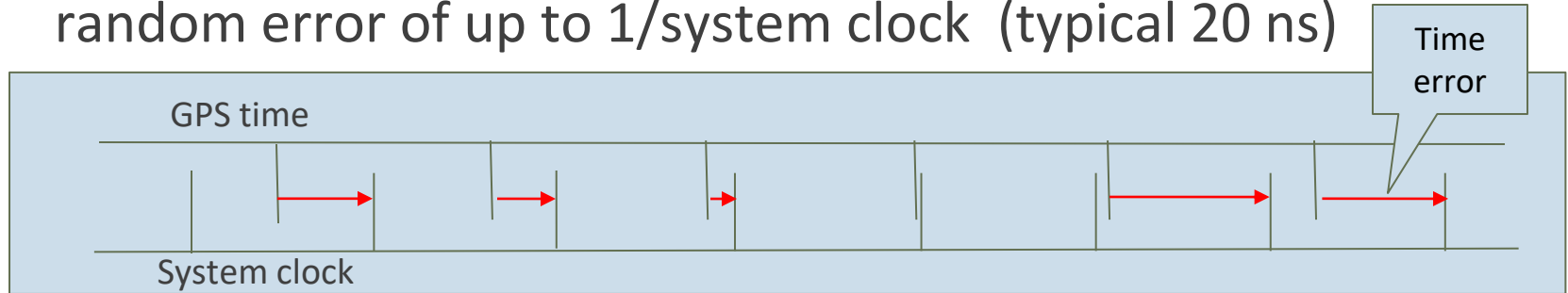
Trace	Notes	Input Freq	Sample Interval	ADEV at 100s	Acquired	Instrument
Chinese GPS		10 MHz	1.000 s	8.80E-11	5257 pts	Picotest/Array U6200A series

- PPS is phase locked to GPS time causing one decade per decade drop of ADEV
  - PPS Stability measured against 1 Hz derived from a Rubidium reference clock
- Up to 20 ns error per measurement period of 1 s equals 5e-8 stability at 1 s
- At 100 s this drops to 1e-10, equal to TCXO stability.

# GPS time error sources(1)

Problem: GPS receiver internal clock frequency:

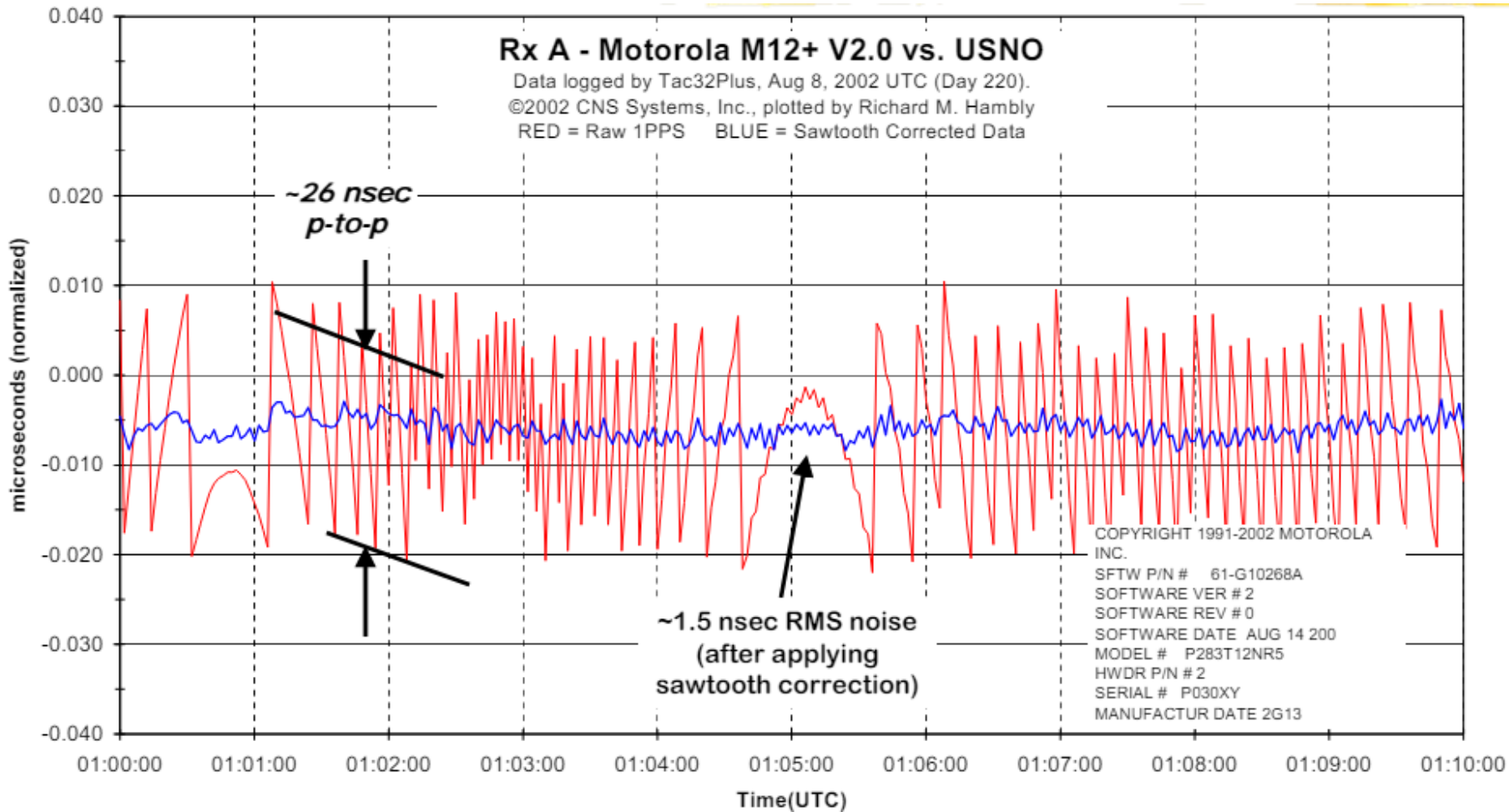
- The 1 PPS output is derived from internal clock causing a random error of up to 1/system clock (typical 20 ns)



Solution: Communicate time error before outputting next PPS

- PPS receiver subtracts communicated time error.
- Improves ADEV to  $1e-11$  @ 100 s (factor 10 improvement)
- This is called “Sawtooth correction”

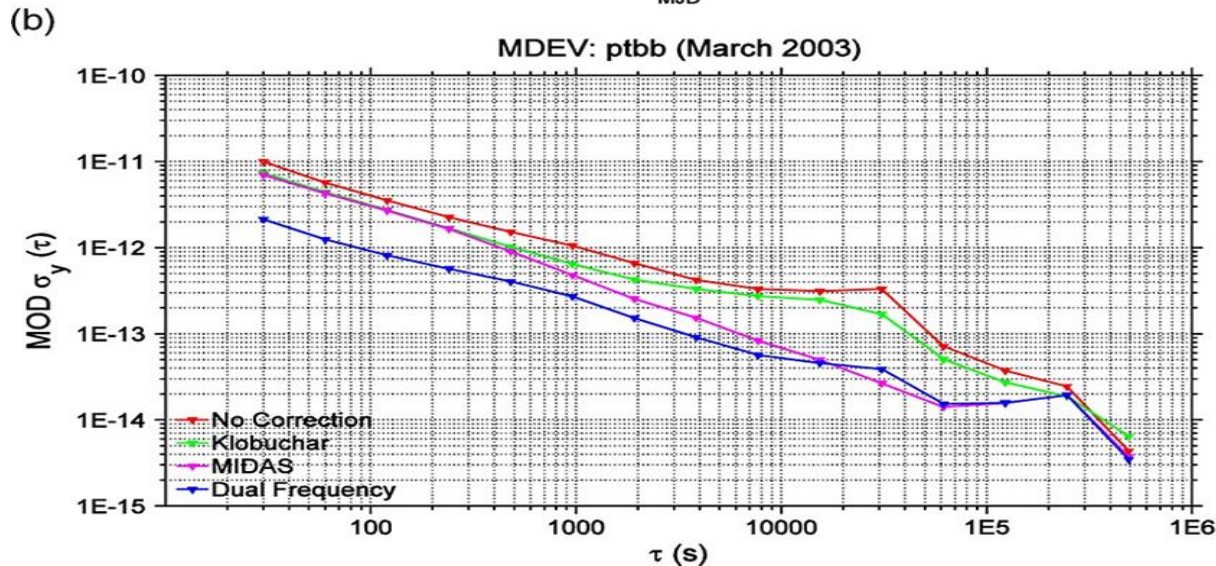
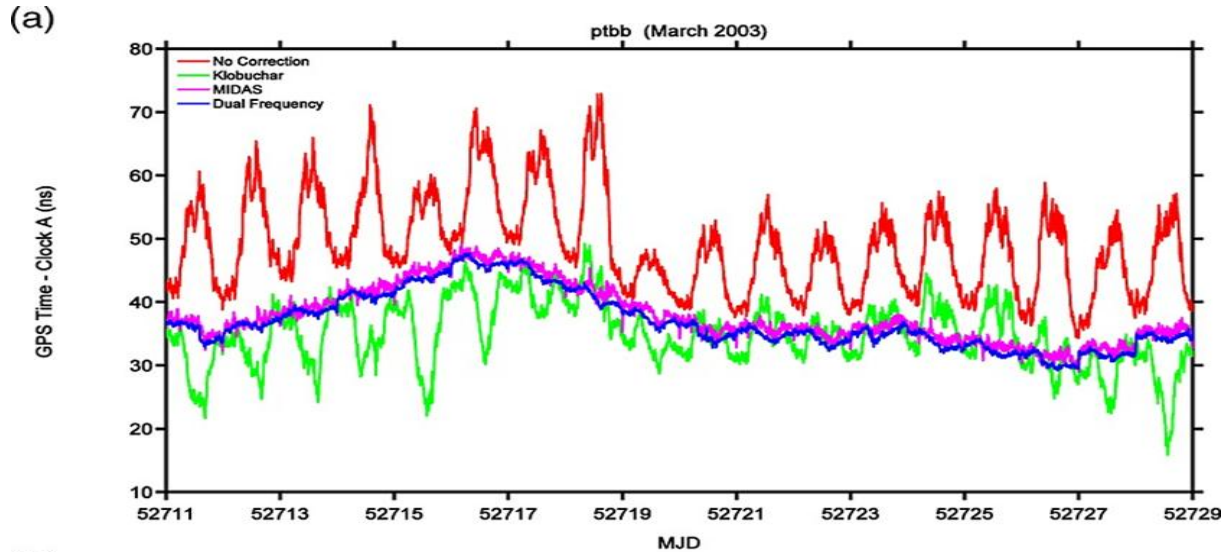
# Impact of sawtooth correction



# GPS time error sources(2)

- Problem: Ionosphere delay varies over time.
  - Daily variation up to 20 ns
  - Ionospheric delay depends on transmitter frequency
- Solution: Use multiple frequency bands to eliminate variations
  - Modern GPS satellites transmit on multiple frequencies.
  - Daily variation can be eliminated but not the long term variation

# GPS ionosphere delay variation



Good multi band receiver  
Can have an ADEV of  
 $1e-12$  @ 100 s

# Design: Main Components

Only TCXO fits in cost/power budget

- OCXO costs most than all other components.
- OCXO can not operate for 5 hours on small battery

Only most basic GPS receiver fits in cost budget

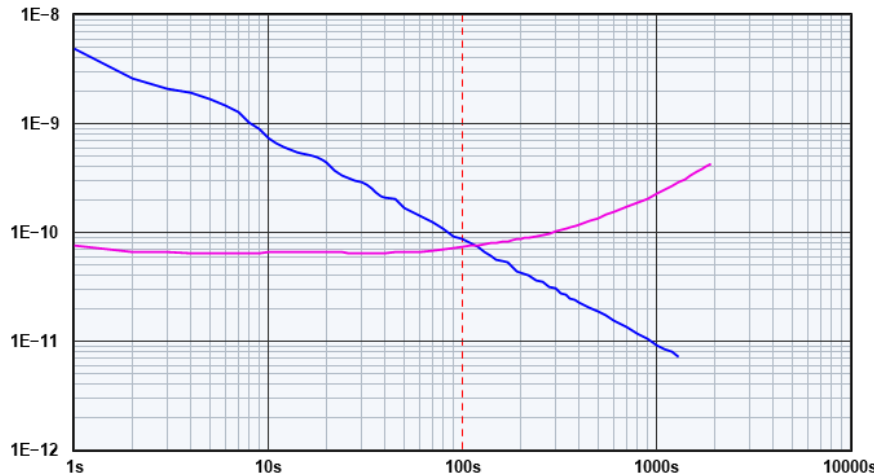
- Receiver with Saw tooth correction and/or multi band receiver costs more than all other tinyGTC components together.

Implication:

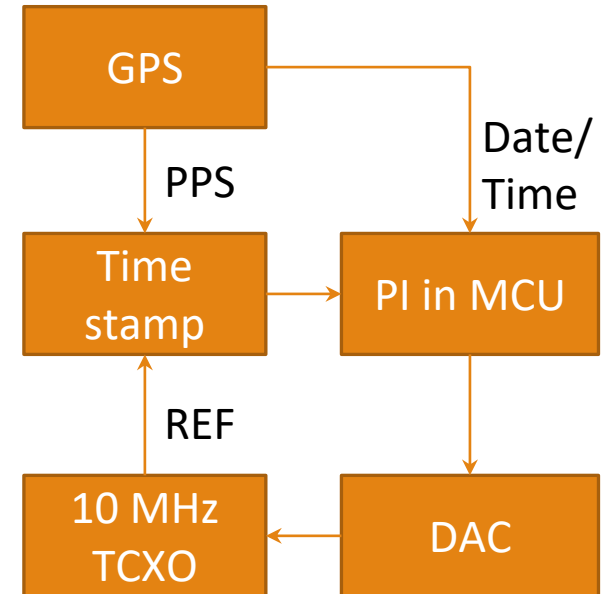
- Use tinyGTC REF input with external reference if you need better stability.

# Design: Architecture

Allan Deviation  $\sigma_y(\tau)$



Trace	Notes	Input Freq	Sample Interval	ADEV at 100s	Acquired
Chinese GPS		10 MHz	1.000 s	8.80E-11	5257 pts
tinyGTC unlocked		10 MHz	1.000 s	7.39E-11	7706 pts

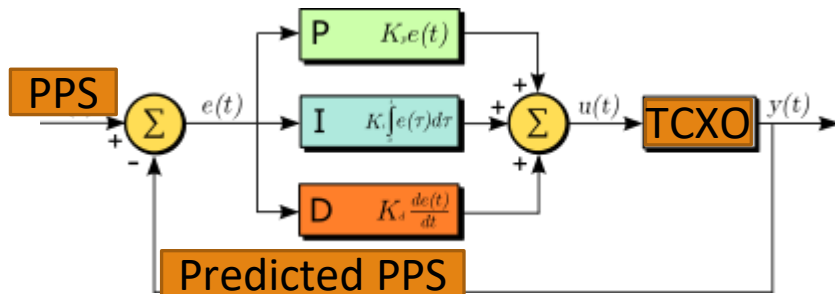


- Use internal TCXO oscillator for short term stability (pink trace)
- GPS provides long term stable PPS output (blue trace))
- PPS timestamped for use in phase detector
- Use slow PI loop to adjust frequency of the TCXO using the DAC
  - Below 100 s TCXO stability dominates
  - Above 100 s GPS time dominates

# Design: Selecting the DAC

- TCXO control range is 200 Hz for 0-2 V
- With 10 MHz output this equals to  $2e-5$  variation
- Minimum DAC step must be well below target ADEV
- Full range / Smallest step = Required DAC resolution
- $2e-5$  (full range) /  $5e-11$  (target smallest step) =  $4e+5$ 
  - Option 1: 16 bit DAC. Not enough resolution
  - Option 2: Summing two 12 bit DAC's 100:1
    - High DAC to reach lock, Low DAC once locked
- Quadruple 12 bit DAC is the cheapest option
  - High DAC with 200 Hz range and  $5e-9$  per step
  - High DAC output noise below  $5e-11$
  - Low DAC with 2 Hz range and  $5e-11$  per step
  - Other 2 DAC's used to set counter trigger levels

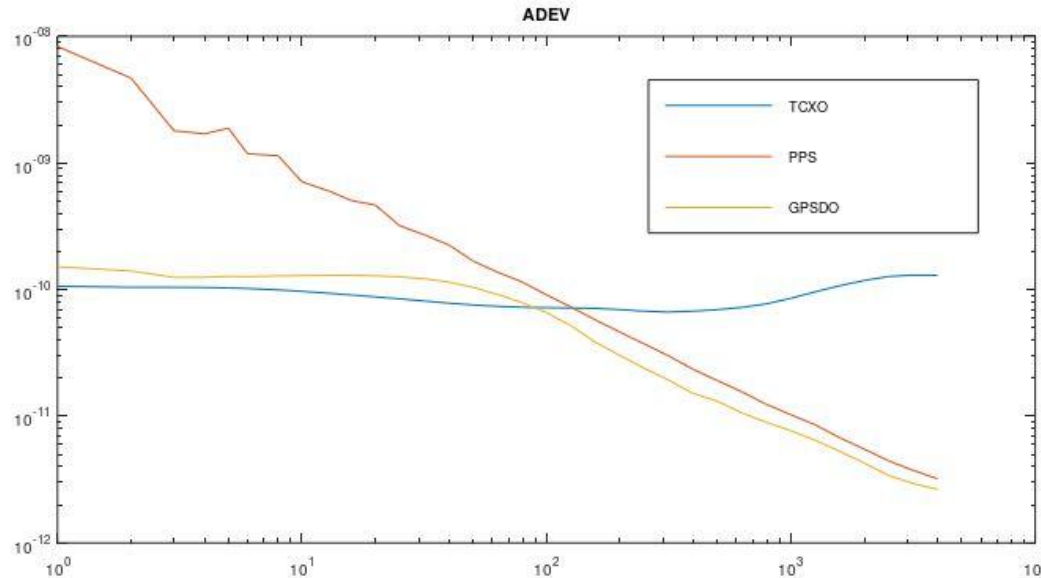
# Design: PI Controller



**Output Change =**  
**(Proportional ( $K_p$ ) \* Frequency Error +**  
**Integral ( $K_i$ ) \* Phase Error) /**  
**loop\_gain(Hz/DAC Step).**

- PI controller acts on measured frequency error and phase error (time difference between predicted PPS time and actual PPS timestamp, equal to integral if frequency error)
- $K_d = 0$  because of large amount of noise in PPS
- $K_p$  and  $K_i$  exclude  $1/\text{loop\_gain}$  factor
- Controller runs every second.
- $K_p$  term causes PPS noise to disturb the TCXO
- This noise raises the ADEV below 100 s.
- Kalman filter before P term can reduce low Tau noise
  - Not yet implemented
- Problem with trial and error method for finding  $K_p$  and  $K_i$  :
  - Measuring ADEV up to 1000 s takes almost one hour

# Simulating the PI controller



Simulation done in Octave  
Requires less than 200 lines of code

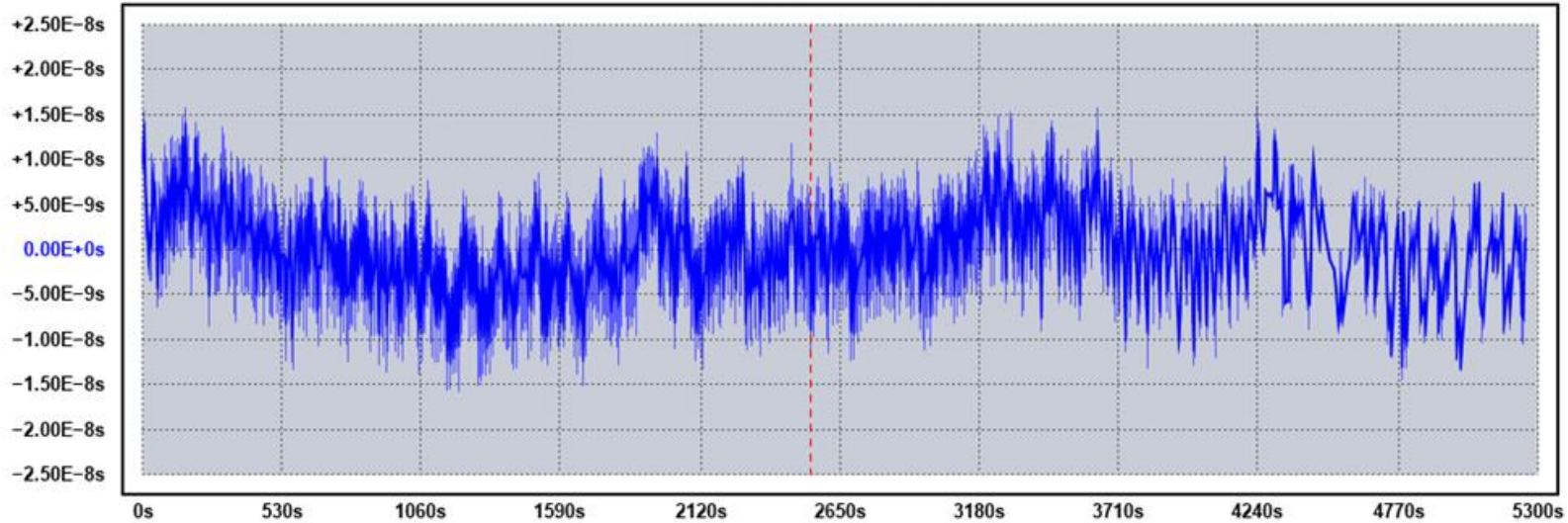
- Simulation uses actual PPS and TCXO stability measurements and control gain as input for model of the PI control loop
- Quick turnaround with alternative control algorithms and parameters (seconds instead of hours)
- Optimal PI parameters established ( $K_p = 0.04$ ,  $K_i = 0.0001$ )
- Control “noise” reduces TCXO performance a bit below 100 s
- GPSDO must control TCXO phase to ensure fastest dropping of ADEV.

# Translating to control

- Measure control gain (Hz per DAC step) for for high/low DAC. This takes care of TCXO differences and aging.
- Problem: TCXO initial frequency can be many Hz wrong and a portable GPSDO should quickly reach below  $1e-9$  frequency error but  $K_p = 0.04$  makes reaching this low error level very slow and  $K_i$  will cause a lot of overshoot.
- Solution: Use multiple controllers
  - Frequency error  $>$  PPS noise level ( $2e-8$ )
    - Use frequency error to control frequency using high DAC
    - $K_p = 1$  and  $K_i = 0$  for very fast reduction of error
    - This quickly drops the error below high DAC step of  $5e-9$
  - Frequency error  $<$  PPS noise level
    - Use phase error to control only low DAC
    - Use  $K_p = 0.04$  and  $K_i = 0.0001$
    - This will keep the phase locked to PPS

# Validating: GPS PPS

Phase Difference (Linear residual)  
Averaging window: Per-pixel



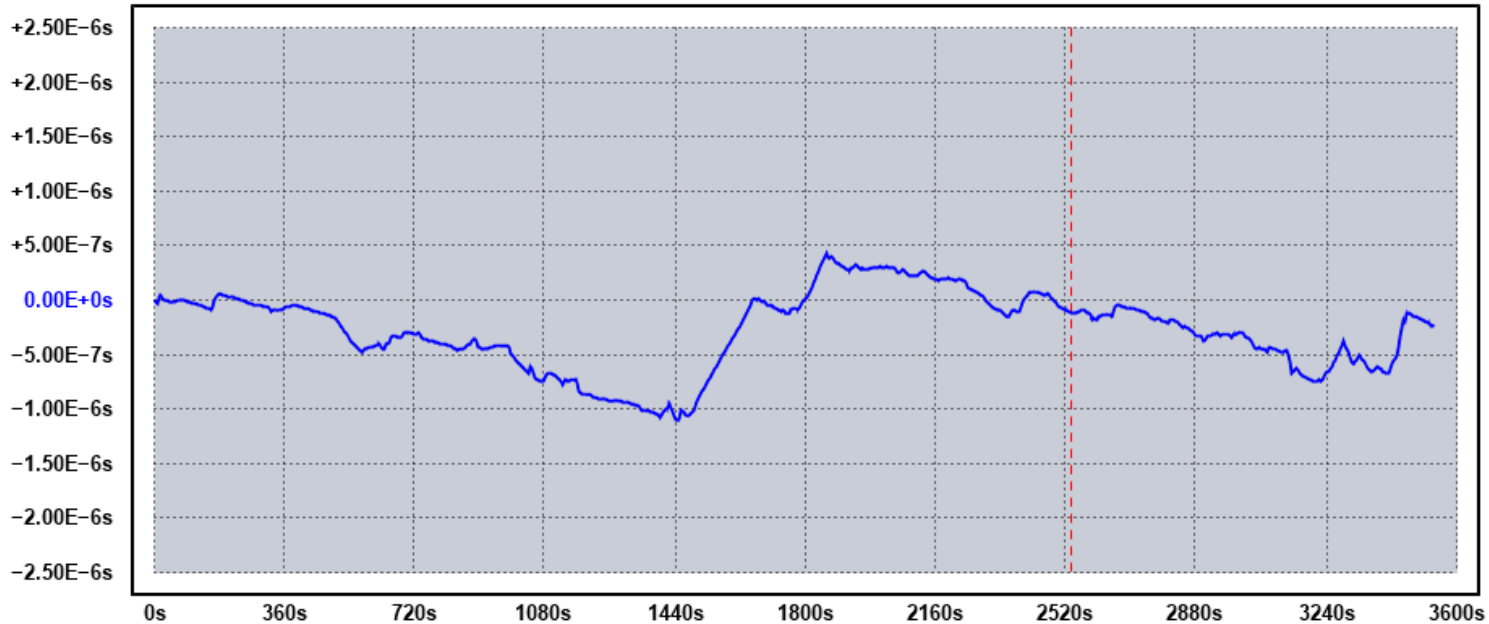
Trace	Notes	Input Freq	Sample Interval	Phase at 2536s	Duration	Elapsed	Acquired	Instrument
Chinese GPS		10 MHz	1.000 s	-1.05E-7s	1h 27m 37s	1h 27m 37s	5257 pts	Picotech/Array U6200A series

- ADEV chart is summary. Also need to check phase variations
- GPS PPS phase measured against 1 Hz derived from 10 MHz Rubidium.
- GPS PPS jitter within 20 ns
- Slow phase variations in line with Ionosphere delay variations (20 ns)

# Impact of bad antenna signal

Phase Difference (Linear residual, zero-based)

Averaging window: Per-pixel



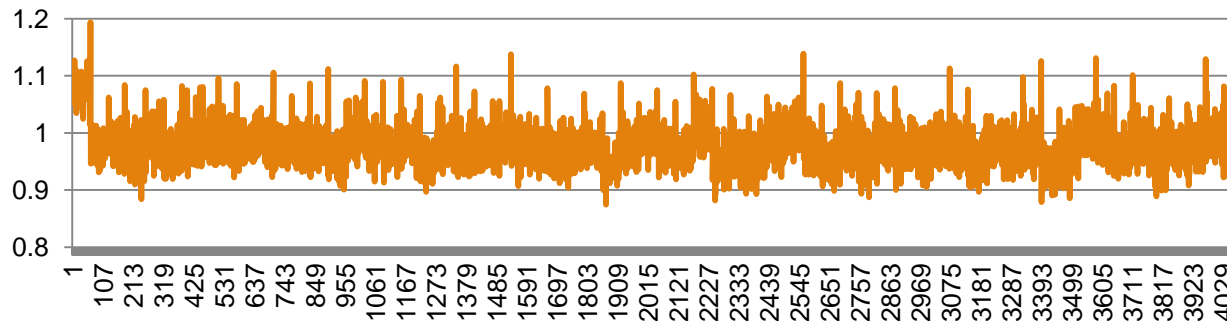
Trace	Notes	Input Freq	Sample Interval	Phase at 2536s	Duration	Elapsed	Acquired	Instrument
PPS bad (Unsaved)		10 MHz	1 s	2.27E-6s	58m 58s	58m 58s	3538 pts	PICOTEST

- Factor 10 higher phase variations: 2.5e-7 instead of 2e-8
- Impossible to discipline the TCXO at 100 s and larger

# Validating: High DAC(1)

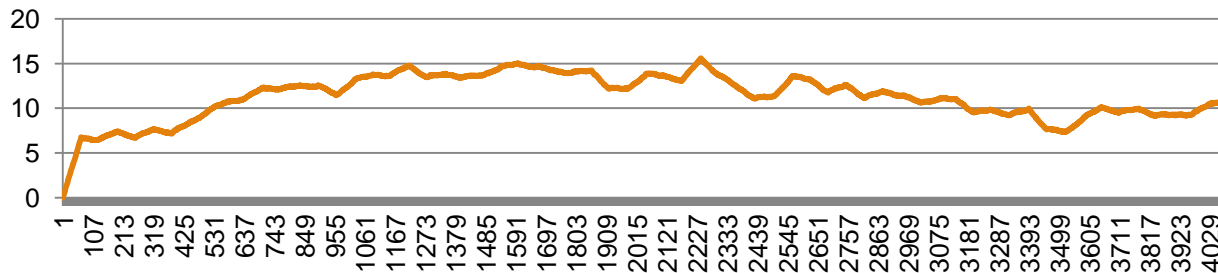
- Step through all DAC output voltage values and check voltage step sizes
  - DAC steps are monotonous

**Normalized Step Size**



- Check for all DAC output values the deviation from linearity
  - Deviation from linear below 0.2 %

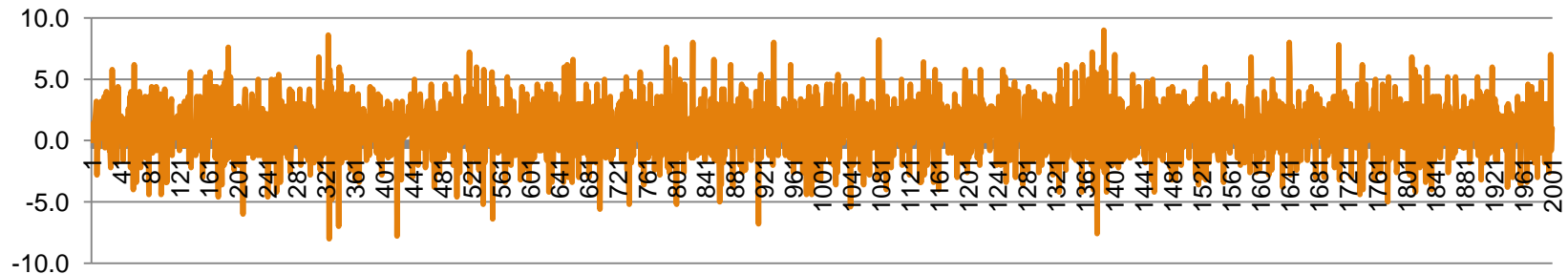
**Normalized Linear Residue**



# Validating: High DAC(2)

- Noise level from high output DAC should be low enough compared to low DAC output
  - Voltage noise average 2 low DAC steps, just acceptable

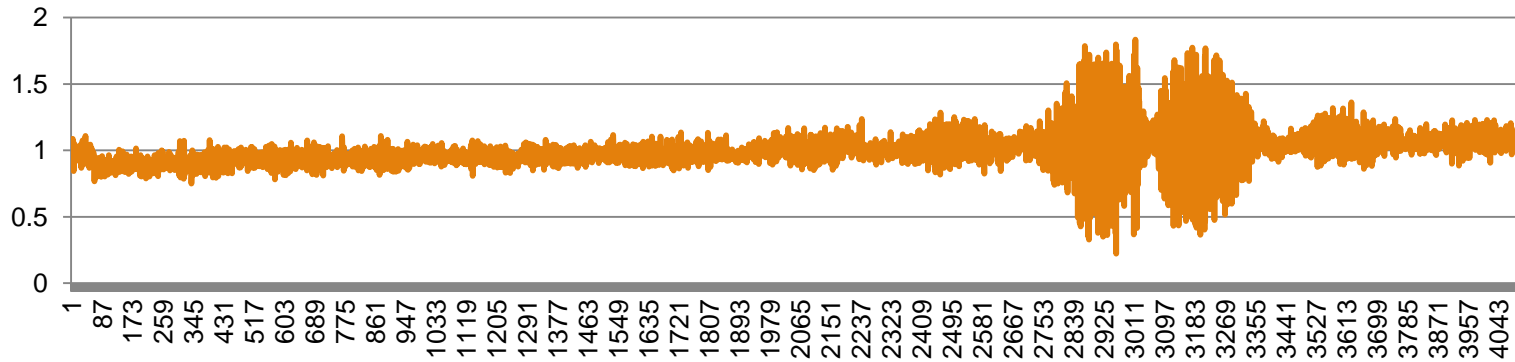
**Summed DAC noise normalized to low DAC voltage step**



# Validating: DAC + VC-TCXO

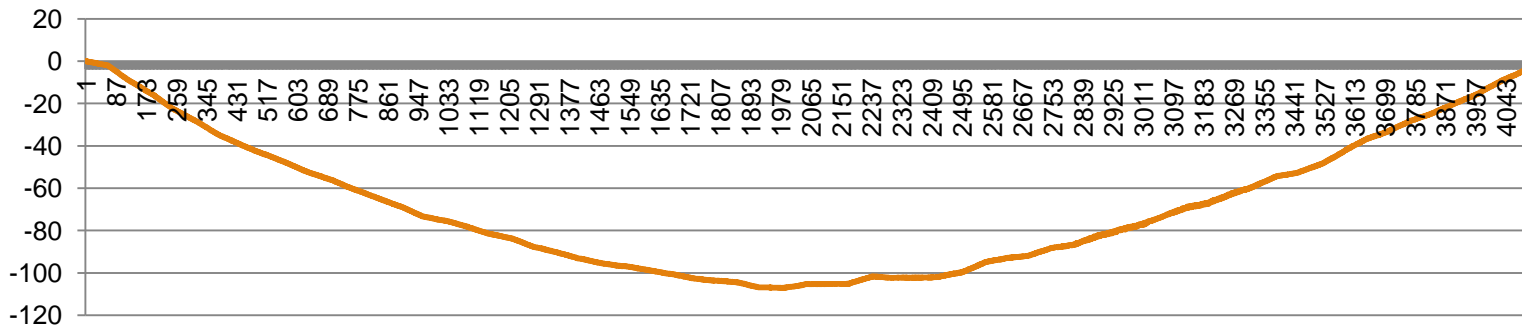
- Step through all DAC output voltage values and check TCXO frequency step
  - Frequency steps also monotonous

**Normalized Step Size**



- Check for all DAC output values the deviation from frequency linearity
  - Frequency deviation from linearity 2.5%, acceptable.

**Normalized Linear Residue**



# Validating: Total system

Allan Deviation  $\sigma_y(\tau)$



Trace	Input Freq	Sample Interval	ADEV at 100s	Duration	Elapsed	Acquired	Instrument
PPS (Unsaved)	10 MHz	1.000 s	9.11E-11	5h 13m 32s	5h 13m 32s	18812 pts	Picotest/Array U6200A series
TCXO (Unsaved)	10 MHz	1 s	7.14E-11	5h 43m 18s	5h 43m 18s	20598 pts	Picotest/Array U6200A series
GPSDO kP=0.04	10 MHz	1.000 s	4.27E-11	5h 14m 28s	5h 14m 28s	18868 pts	Picotest/Array U6200A series
GPSDO kP=0.02	10 MHz	1.000 s		4h 8m 50s	4h 8m 50s	14930 pts	Picotest/Array U6200A series

- Green trace is GPSDO performance against a Rubidium reference
- Multiple PI parameters tested to check design robustness
- Phase lock reached within 35 seconds
- Actual performance in line with simulation within statistical uncertainty

# Questions

